

# InP/GaAsSb/InP DHBTs WITH HIGH $f_T$ AND $f_{MAX}$ FOR WIRELESS COMMUNICATION APPLICATIONS

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## Abstract

We study the DC and microwave performance of MOCVD-grown carbon-doped InP/GaAsSb/InP double heterojunction transistors (DHBTs) with high cut-off frequencies. A maximum cutoff frequency of 106 GHz is obtained while maintaining a relatively high breakdown voltage ( $BV_{CEO} = 8$  V) in devices with a 2000 Å InP collector. In these devices, the maximum frequency of oscillation is limited by the GaAsSb base sheet resistance (which is high in comparison to GaAs or GaInAs conventional bases), and high  $f_{MAX}$  values can only be achieved by scaling the devices to simultaneously reduce the total base resistance  $R_B$  and the base-collector capacitance  $C_{BC}$ . A new self-aligned process was developed which results in  $f_T = 80$  GHz and  $f_{MAX} = 90$  GHz for devices with a 3000 Å collector and a 1  $\mu$ m emitter stripe fabricated by contact lithography and all-wet etching.

## I. Introduction

InP/GaInAs and AlInAs/GaInAs -based single heterojunction bipolar transistors (SHBTs) have demonstrated impressive microwave characteristics but suffer from low collector breakdown voltages and high output conductance because of the narrow bandgap GaInAs collector. Double heterojunction HBTs with widegap InP or AlInAs collectors improve breakdown properties but are limited by collector current blocking due to the conduction band discontinuity at the base-collector (BC) junction. Various doping and/or compositional grading schemes have been developed to eliminate the BC current blocking effect, but such conventional approaches impose stringent growth uniformity requirements to achieve uniform device yields across a wafer. Unless care is exercised in device design and implementation, the collector traveling space charge associated with high collector current densities reveals a retarding or blocking potential at the BC junction even if the BC interface is graded to smooth out its conduction band discontinuity.

We recently demonstrated well-behaved MOCVD-grown C-doped abrupt heterojunction InP/GaAsSb/InP DHBTs which feature a very small  $V_{CE}$  offset voltage  $< 20$  mV and a low turn-on voltage ( $J_C = 1$  A/cm<sup>2</sup>) of  $V_{BE}$

= 0.4 V [2], by taking advantage of the staggered band lineup at InP/GaAsSb interfaces [3].

Fig. 1 shows the equilibrium energy band diagram of an InP/GaAsSb/InP DHBT. The GaAsSb conduction band lines up above that of InP with  $\Delta E_C \sim 0.15$  eV at 300K. There is no conduction band spike at the emitter-base abrupt heterojunction, and the valence band discontinuity is  $\Delta E_V = 0.78$  eV. The GaAsSb band-gap is 0.72 eV at room temperature [3].

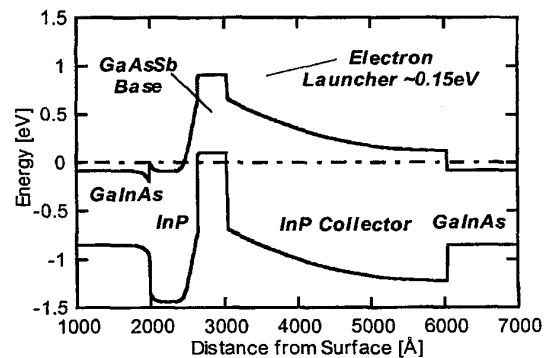


Fig. 1: Band diagram at equilibrium for an InP/GaAsSb/InP DHBT. The electron injection into the base is thermal, and there is no blocking at the BC heterojunction.

With a band diagram such as that of Fig. 1, electrons are injected into the GaAsSb base thermally, and thus cross the base by diffusion without the hot electron transport observed in abrupt emitter (Al,Ga)As/GaAs, InP/(Ga,In)As or (Al,Ga,In)As/(Ga,In)As HBTs. On the other hand, the band diagram suggests that electrons get injected into the InP collector layer with a high initial velocity corresponding to the  $\Delta E_C \sim 0.15$  eV. The large valence band discontinuity at the InP/GaAsSb interface also suppresses minority carrier back injection into the InP emitter. Similarly, the band lineup prevents hole injection into the InP collector in the saturation mode and/or at high current densities due to the conventional Kirk effect. The InP collector layer and the absence of (Al,Ga,In)As or (Ga,In)(As,P) quaternary grading layers at the base-collector junction both reduce the thermal resistance of the collector layer because of the high thermal conductivity of InP in comparison to III-V alloys. In addition, the InP collector should display high field electron drift velocities that exceed those found in GaAs while enabling high collector breakdown voltages as a result of the high breakdown field in InP.

In the present work, we report a study of the DC and microwave performance of MOCVD-grown carbon-doped InP/GaAsSb/InP double heterojunction transistors (DHBTs) with various collector thicknesses. Thicker collector devices exhibit an earlier roll-off of  $f_T$  at higher current densities which is reminiscent of the Kirk effect. Scaled devices display high  $f_{MAX}$  and  $f_T$  values that make them attractive components for long talk-time wireless communication devices.

## II. Device Growth and Fabrication

### A. Epitaxial Growth

DHBT structures with three different collector thicknesses were grown on nominally exact SUMITOMO (001) InP:Fe substrates in a horizontal low pressure MOCVD system equipped with a quartz chamber. Pd-diffused  $H_2$  with a total flow of 6 SLM served as the carrier gas at a reactor pressure of 100 Torr. TMIIn, TEGa, TMSb, TBAs and TBP were the precursors.  $H_2S$  and  $CCl_4$  were used for *n*- and *p*-type doping. Device structures consist of a 500Å  $Ga_{0.47}In_{0.53}As$  subcollector (S:  $1 \times 10^{19} \text{ cm}^{-3}$ ), a 2000 Å (3000 Å, or 5000 Å) InP collector (S:  $< 1 \times 10^{16} \text{ cm}^{-3}$ ), a 400 Å  $GaAs_{0.51}Sb_{0.49}$  base (C:  $4 \times 10^{19} \text{ cm}^{-3}$ ), a 1500 Å InP emitter (S:  $3 \times 10^{17} \text{ cm}^{-3}$ ), a 500 Å InP layer (S:  $3 \times 10^{19} \text{ cm}^{-3}$ ) and a 2000 Å  $Ga_{0.47}In_{0.53}As$  Ohmic contact layer (S:  $1 \times 10^{19} \text{ cm}^{-3}$ ).

These growth conditions result in typical base sheet resistances of 1400-1800  $\Omega/\square$  because of strong alloy

scattering for holes in GaAsSb. On the other hand, antimonide compounds generally display low hole Schottky barrier heights  $\phi_p$  when compared to arsenides and phosphides, and one would thus expect very low base contact resistances. TLM measurements (not shown) for a Pt/Ti/Pt/Au non-annealed Ohmic contact on a 400 Å GaAsSb base layer indeed reveal low base specific contact resistances in the  $10^{-8} \Omega\text{cm}^2$  range despite a sheet resistance of  $\sim 1400\Omega/\square$ . The low base contact specific resistance is very important advantage for the fabrication of aggressively scaled sub-micrometer emitter HBTs where the specific contact resistance can sometimes dominate  $R_B$ .

### B. DC Characterization

Large area InP/GaAsSb/InP DHBTs ( $80 \times 80 \mu\text{m}^2$ ) were fabricated on the three layers to assess the epitaxial material quality. Fig. 2 shows typical  $I_C(V_{CE})$  characteristics for a DHBT with a 5000 Å thick collector. The device shows a breakdown voltage  $BV_{CEO}$  approaching 15V and small output conductance.

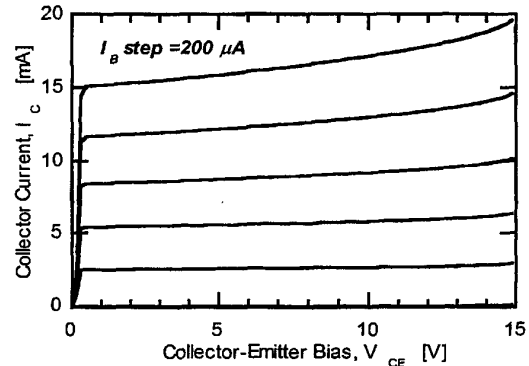


Fig. 2: Typical  $I_C$ - $V_{CE}$  characteristic for a large area ( $80 \times 80 \mu\text{m}^2$ ) InP/GaAsSb/InP DHBT with 5000Å thick InP collector.

Small area DHBTs were fabricated using a simple triple-mesa self-aligned process described in [4]. Ti/Pt/Au and Pt/Ti/Pt/Au was used as Ohmic contacts on the emitter and the base respectively. We measured 15V, 10V and 8V breakdown voltages (defined at  $I_C=100 \mu\text{A}$ ) for DHBTs with 5000Å, 3000Å and 2000Å InP collectors.

### B. Microwave Characterization

#### (1) Wide Emitter Stripe Devices ( $4 \times 12 \mu\text{m}^2$ )

On-wafer microwave *S*-parameter measurements were performed, on  $4 \times 12 \mu\text{m}^2$  DHBTs, between 0.5 GHz and 40 GHz with an HP8510 network analyzer equipped with GGB Model 40A Picoprobes. The extracted peak current gain cutoff frequencies are 106 GHz, 82 GHz and 40 GHz for the 2000 Å, 3000 Å

and 5000 Å thick collectors. Note that the 106 GHz cutoff frequency is by far the best  $f_T$  ever reported in this material system, and was achieved while maintaining a relatively high breakdown voltage ( $BV_{CEO} = 8$  V). The lower cut-off frequencies obtained for the 3000 Å and 5000 Å collectors are attributed to an increased collector transit time  $\tau_c$ , and to a Kirk-like limitation due to space charge effects in the lightly doped InP collectors used here. This limitation is particularly significant for the 5000 Å thick collector since the collector doping was nominally identical for all layers at  $N_D < 10^{16}$  cm<sup>-3</sup>.

The relation between collector space charge effects and the decreased peak  $f_T$  values achieved with thicker InP collectors is confirmed by the  $f_T(I_C)$  dependence of these devices: thicker collectors result in lower peak  $f_T$  current densities (not shown). Also, a plot of the extracted minimum transit time  $\tau_F$  as a function of collector thickness would show that  $\tau_F$  increases superlinearly with increasing collector thickness  $W_C$ , in marked contrast to the  $W_C/2v_{sat}$  dependence one would expect from a simple increase of the collector transit time with a saturated velocity collector.

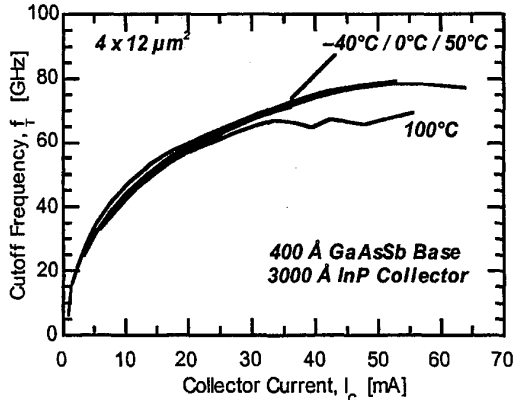


Fig. 3: Temperature dependence of  $f_T$ . Measurements taken at Nortel Networks.

The temperature dependence of  $f_T$  was measured at Nortel Networks between  $-40^\circ\text{C}$  and  $100^\circ\text{C}$  for a 3000 Å collector device by performing  $S$ -parameter measurements as a function of temperature. Fig. 3 shows that a slight reduction in peak  $f_T$  is measured at high temperatures while the RF performance remains essentially constant over much of the temperature range.

## (2) Scaled Devices ( $1 \times 24 \mu\text{m}^2$ )

As first discussed in [2],  $4 \mu\text{m}$  emitters lead to low maximum oscillation frequencies because of the high base sheet resistance of GaAsSb layers. To overcome this limitation, devices with laterally scaled dimensions

were fabricated in order to minimize the base spreading resistance and base-collector capacitance. Fig. 4 shows the RF measurement results for a scaled down  $1 \times 24 \mu\text{m}^2$  emitter and  $2 \times 24 \mu\text{m}^2$  base-collector area DHBT. A cutoff frequency of  $f_T = 80$  GHz and a maximum oscillation frequency  $f_{MAX} = 90$  GHz were determined by extrapolation at  $-20$  dB/dec for a 3000 Å collector. The much improved  $f_{MAX}$  was achieved by reducing both the base spreading resistance and the base-collector capacitance to compensate for the high sheet resistance of the GaAsSb base.

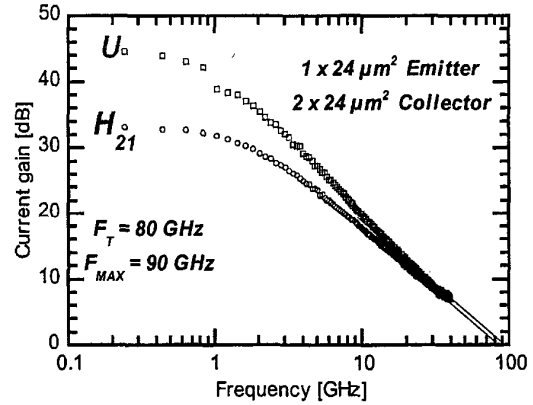


Fig. 4: Extracted cutoff frequencies for an InP/GaAsSb/InP DHBT with a 400 Å base and a 3000 Å InP collector at  $V_{CE} = 1.5$  V.

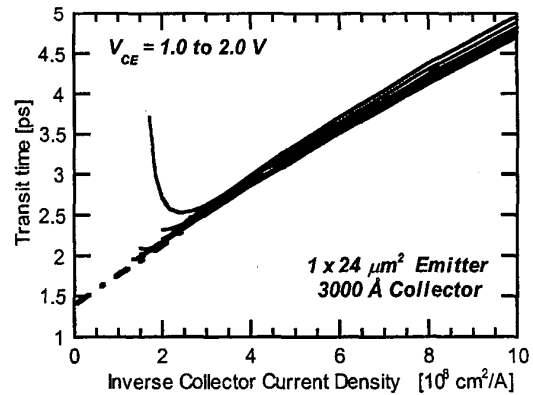


Fig. 5: Transit time versus inverse collector current density. The minimum transit time extrapolates to 1.4 ps at infinite current.

Fig. 5 is a plot of the forward transit time  $\tau_F$  dependence upon  $1/J_C$  and shows a minimum transit time of  $\tau_F = 1.4$  ps extrapolated at  $1/J_C = 0$ . It is interesting to note that the transit time does not exhibit a dip at high current densities like it commonly does in conventional single heterojunction HBTs because of the reduced collector electric field induced by the electron traveling space charge.

### (3) Potential Ultimate Frequency Performance

Our progress with InP/GaAsSb/InP DHBT performance has been swift: from initial devices with an  $f_T$  of 20 GHz in early 1998 [unpublished], we first reported devices with  $f_T = 70$  GHz and a low  $f_{MAX} = 20$ -25 GHz [2], and followed up with the present results. This rapid progress naturally raises the question of the ultimate cutoff frequency in this material system.

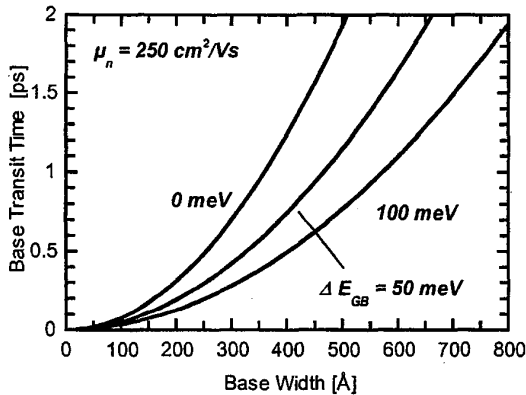


Fig. 6: Effect of base grading on the base transit time  $\tau_B$ .

As discussed above, electrons are thermally injected from the InP emitter into the GaAsSb base and cross it by diffusion, without the benefit of non-equilibrium base transport seen in conventional abrupt emitter HBTs. Two mutually compatible options are then available to further reduce the total transit time: *a*) A hot electron launcher emitter with a positive  $\Delta E_C$  value with respect to GaAsSb; and/or *b*) Incorporate a graded base layer to base transit time. The first solution can be implemented with an AlInAs emitter which would provide  $\Delta E_C \cong 0.10$  eV with respect to the GaAsSb conduction band edge according to transitivity—the effects of such an emitter are difficult to predict because there currently is no readily available information on the hot electron transport properties of GaAsSb. On the other hand, the effect of energy gap grading on the base transit time can easily be estimated. In the following, we make use of a drift/diffusion model for transport across the base [5] and assume an electron mobility  $\mu_n = 250$  cm<sup>2</sup>/Vs estimated from the majority carrier electron mobility values reported in [6]. The low electron mobility in GaAsSb layers and the diffusive transport across the base suggest a significant fraction of the transit time is made up of  $\tau_B$ . However, modest amounts of band gap grading across the base greatly reduce  $\tau_B$ : a  $\Delta E_{GB} = 0.1$  eV reduces the base transit time from 1.24 ps down to 0.49 ps, suggesting that  $f_T$ 's as high as 200 GHz might be possible. The necessary energy gap grading should be implemented relatively easily through the incorporation of as little as a ~10%

Al mole fraction in the base layer to form an (Al,Ga)As<sub>0.51</sub>Sb<sub>0.49</sub> graded base lattice-matched to InP.

### III. Conclusion

We have developed and characterized high performance InP/GaAsSb/InP DHBTs grown by MOCVD. The DHBTs show excellent breakdown voltages and high-frequency performances with demonstrated  $f_T$  of over 100 GHz. Devices with  $f_T = 80$  GHz and  $f_{MAX} = 90$  GHz were realized by scaling the transistor dimensions laterally to a 1  $\mu$ m emitter stripe with 0.5  $\mu$ m effective base contacts implemented by contact photolithography. The devices exhibit attractive properties for application in long talk-time wireless communication systems, and even better results should be possible by further device scaling and the incorporation of base quasi-electric fields to further reduce the base transit time.

### Acknowledgments

This work was supported by an NSERC Strategic Grant and by equipment and research grants from Hewlett-Packard Research Laboratories (Palo Alto, CA). We wish to thank Mr. T.W. MacElwee of Nortel Networks (Ottawa, ON) for the measurements of Fig. 3. The support and encouragement of Dr. Nick Moll (HP) and Mr. Robert Hadaway (Nortel) is gratefully acknowledged.

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